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GPS Survey of the Western Tien Shan

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REPORT ON THE TIEN SHAN GLOBAL POSITIONING EXPERIMENT, JUNE-JULY 1993

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This report summarizes the background, field work, data collection and analysis, and future plans associated with a collaborative GPS experiment in the Tien Shan of the former Soviet Union. This project involves the amalgamation of two, separately funded projects, which were proposed separately by PIs Hamburger and Reilinger (NSF no. EAR-9115159 and NASA no. NAG5-1941) and Molnar and Hager (NSF no. EAR-9117889 and NASA no. NAG5-1947). In addition, the work is being conducted under the auspices of the US-USSR Agreement on Cooperation in the Field of Environmental Protection, with support from the United States Geological Survey.

The results reported here comprise the fruition of several years of discussions and preparation. Whereas geodetic measurements by foreigners were categorically impossible in the Soviet Union, we are now carrying out large-scale field programs with the encouragement and support of numerous agencies in the various republics that now form the Commonwealth of Independent States (CIS). We omit a detailed summary of the various discussions that have enabled us to do serious geodetic work; most of this has been described in previous reports. Suffice it to say that we have written agreements with essentially all agencies actively pursuing geodetic, geophysical, and geological study of the Tien Shan. The list of collaborators tabulated at the end of this document (Table 1) is a testament to the extent of this collaboration. Moreover, in these times of economic hardship in the former Soviet Union, our project has been sufficiently well received that the majority of the field expenses have been borne by our colleagues there. Although they may not be able to continue this support in future years, we think that this commitment demonstrates a strong interest in our joint project.

BACKGROUND AND GENERAL SCIENTIFIC OBJECTIVES

We began field work in July, 1992, with a small-scale pilot experiment in the northern Tien Shan, in the Republics of Kazakhstan and Kyrgyzstan. A 7-week field experiment in June - July, 1993, constituted a major expansion of this pilot network. The field program included reconnaissance and installation of benchmarks of regional GPS sites in Kazakhstan and Kyrgyzstan, a comprehensive training program for collaborating scientists, and an 18-day observation campaign covering the newly installed 86-station geodetic network. The network is closely tied to a regional GPS network established by the German GeoForschungZentrum geodetic group (GFZ), under the direction of Christof Reigber, and Kazakh, Kyrgyz, Russian, and Uzbek scientists. Hereafter, we refer to this network as the "GFZ-CIS regional network."

Building on the GFZ-CIS regional network, we sought to densify part of this network and to extend it eastwards. As the world's most prominent intracontinental mountain belt, the Tien Shan provides an outstanding natural laboratory to address two general problems in intracontinental geodynamics: (1) the processes by which distributed intracontinental shortening occurs, and (2) the mechanisms that allow strain to be absorbed adjacent to an intracontinental strike-slip fault along which slip varies markedly. Moreover, with a high level of seismicity and with rapid deformation, the Tien Shan offer the potential for witnessing pre- and post-seismic deformation and the opportunity to study localized deformation within the regional framework of intracontinental tectonics.

Intracontinental mountain building. The present range owes its height and high level of seismic and tectonic activity to roughly north-south crustal shortening. Hence, it serves as a prominent consequence of India's collision with and subsequent penetration into the Eurasian Plate (Figure 1). Yet, this area lies 1000-2000 km from the northern edge of the Indian plate, and hence deformation should be largely unaffected by peculiarities of the ancient plate margin. Thus, the Tien Shan provides a laboratory to study intracontinental shortening without the influence of asymmetries of kinematics and structure established at the time of the collision, as are clear, for example, in the Himalaya and the Alps.

Approximately two thirds of our network spans a segment of the Tien Shan where the structure is relatively simple. Ranges and intervening basins trend nearly east-west. Blocks of crust, with east-west dimensions of approximately 100 km or more, constitute ranges that are thrust over other blocks to form basins. North-south dimensions of such blocks of only 20-30 km are comparable to the depths to the more ductile lower crust. We anticipate that a comprehensive study of the velocity field in this region will allow us to study the interconnections of the block movements and deformation at depth and to understand how the penetration of India into the rest of Eurasia is communicated to the areas farther north.

Strike-slip geodynamics. The Tien Shan offers a good example of a second feature peculiar to intracontinental deformation. A major strike-slip fault, the Talaso-Ferghana fault, truncates the western part of the region (Figure 1). The east-west trending blocks and the faults between them seem to be cut off by the Talaso-Ferghana fault. Moreover, the Talaso-Ferghana fault ends in the northwestern part of the Tien Shan. In oceanic regions, transform faults, along which slip is constant, abruptly truncate at spreading centers and subduction zones. In continental regions, however, strike-slip faults do not end abruptly, but seem to "die out" by distributed, permanent deformation on one or both sides of the fault. The Talaso-Ferghana fault is perhaps the world's premier example of such an intracontinental strike-slip fault. Slip seems to be rapid, possibly 10 mm/yr. Yet, the fault passes from being a major structure to being absent in a distance of only 100 km. Bounding the fault on both sides are high ranges suggestive of rapid crustal shortening, but also possibly reflecting rapid rotations about vertical axes. The geometry of deformation permits us to determine the kinematics of deformation using GPS. This kinematics should facilitate an understanding of the importance of the relative strengths of the brittle layer at the surface and the region below it that flows ductilely.

GPS GEODESY IN THE TIEN SHAN

GPS Network

Our collaborative GPS project in the Tien Shan began in the summer of 1992 with establishment and observation of a 13-station "pilot network," covering an area of approximately 300 x 200 km^2 across the northern flank of the Tien Shan (shown as gray circles in Figure 2). This network, largely restricted to southern Kazakhstan but with one station within the Kungei Alatau range in northern Kyrgyzstan, was designed to measure rates of deformation across the northern ranges of the Tien Shan with respect to a relatively stable area, the southeastern part of the Kazakh platform, in the north. At nearly the same time, the GFZ group, in collaboration with scientists from Kazakhstan, Kyrgyzstan, Russia, and Uzbekistan, installed and measured their 42-site GFZ-CIS regional network (shown as white circles in Figure 2), which extends from the Turan Platform of central Uzbekistan in the west across the central Tien Shan, and from the northern Pamir to the southern edge of the Kazakh Platform. Our pilot network shared three sites of the GFZ-CIS regional network, allowing us to tie the two networks together.

We carried out our major field program in June-July, 1993, relying on contributions from over fifty scientists, representing ten scientific organizations from four countries (Table 1). Reconnaissance for the field experiment in June included the installation of new benchmarks and the verification of existing marks. Four field parties selected and installed 55 new geodetic benchmarks, consisting of steel pins set in bedrock with epoxy. A small number of marks were mounted in boulders or in concrete piers in unconsolidated sediment. Reference marks were also set at a number of existing sites. Six of the sites in Kazakhstan used geodetic marks of the national geodetic control network, two were placed near such marks, and another 2 were co-located with benchmarks of local networks established by the Institute of Seismology of Kazakhstan. We collected data at 86 stations distributed over an area approximately 350 km x 550 km, including 59 sites in Kyrgyzstan and 27 sites in Kazakhstan (Table 2 and black triangles in Figure 2). The geometry of the network was designed to focus on the two basic questions discussed above and consists of two large sub-networks.

The larger of the two subnetworks includes approximately 55 sites distributed across the Tien Shan between longitudes 75° E and 79° E, from near the border with China in the south, northward onto the Kazakh platform. This sub-network can be considered as consisting of two north-south profiles, one passing just west of the lake Issyk-Kul, and the other just east of the lake and west of the Chinese border where the border trends north-south. Moreover, this eastern sub-profile extends the "pilot" network installed in 1992 southward. The guiding principle in the installation of this subnetwork was that at least two, and wherever possible, 3 or more, sites should lie on each of the major east-west-trending crustal blocks in this part of the Tien Shan so that we can determine both translations and rotations of individual blocks.

The second sub-network consists of 30 stations surrounding the northwest termination of the Talaso-Ferghana fault. It was designed with the same principal of placing at least two sites on each major crustal block. In addition, we sought a network that extends at least 100 km perpendicular to the fault in order to help isolate elastic strain accumulation associated with slip at depth on the Talaso-Ferghana fault. This network extends from the Kazakh Platform in the north to the Ferghana Basin in the south, and from the western ends of the Chatkal Ranges west of the Talaso-Ferghana fault eastward to Bishkek. Depending upon how one defines the stable Kazakh Platform in the northern part of region studied, 5 to 7 sites lie on this block, which should define a stable reference frame attached to the Eurasian Plate.

The sites observed in 1992 included remeasurements of 12 of the sites observed during the 1992 pilot GPS experiment and over 10 coinciding with the GFZ-CIS regional geodetic network (Figure 2). These ties permit both (1) independent measurements of base lines common to the two networks and (2) preliminary estimates of repeatabilities from comparisons between sites common to the 1992 and 1993 campaigns. Results from both make us optimistic about the science that will result from the repeat survey in 1995.

Field Measurements

In July, 1993, observations were conducted over 18 consecutive days using 18 sets of GPS receivers: 10 Trimble 4000SSEs (P/X code) and 8 Trimble 4000SSTs (C/A code). We recorded round-the-clock in five 60-hour sessions and one 42-hour session. Automobile batteries, rated as 90 amp-hour and charged by solar panels, powered the receivers. Receivers remained at two sites throughout the 18-day recording period: one at the IVTRAN test site near Bishkek, which is near the center of the network, and the other at Kuldjabash, which is a GFZ-CIS site near the Chinese border and near the center of the southern edge of the network. In addition, we used another six "semi-fixed" sites to provide continuity to the network geometry, recording at them during 2, 3, or 4 consecutive 60-hour sessions. We organized the observation schedule into clusters of sub-networks that migrated, as a "wave," from east to west (Table 2). This maximized the number of relatively short base lines and permitted logistical support among neighboring observation teams. The GPS receivers operated nearly flawlessly for the duration of the experiment, with only minor losses of data due to late starts (primarily due to bad weather and resulting poor road conditions) and to temporary power losses.

The UNAVCO Facility provided direct support to the field experiment through the participation of Brennan O'Neill, Project Engineer for the Tien Shan experiment. O'Neill obtained necessary export licenses for GPS field equipment and arranged shipping to and from the CIS. (Following a major shipping delay caused by an error on the part of the U.S. shipping agent, the UNAVCO office helped ensure that all equipment arrived with only minor delay of the field experiment.) He also provided maintenance of GPS field equipment before and during the field campaign; and took the lead in training approximately 20 Soviet operators and a number of additional participants. Soviet geodesists were primary observers for seven instruments in the field campaign, and many of the secondary observers in 1993 will be primary observers for the repeat measurements in 1995. Finally, O'Neill operated the fixed receiver at the IVTRAN polygon for 18 days.

We cannot overstate the extent to which the success of our work depended on the contributions of our collaborators from the former Soviet Union. The Institute of High-Temperature Physics (Russian Academy of Sciences, "IVTRAN", under the direction of

Yuri Trapeznikov), together with the Kyrgyz State Agency for Geodesy and Cartography ("Kyrgyzgeodeziya", Valery Tsurkov, director) and the Kazakh Central Administration for Geodesy and Cartography ("Kazgeodeziya", Valery Ostroumov, director), coordinated the logistical support for the field experiment, including: (1) arranging import/export customs for all field equipment; (2) obtaining permission to carry out the experiment and process the data in the U.S.; (3) arranging for ground transportation for personnel and equipment from Alma-Ata (Kazakhstan) to the training site outside of Bishkek (Kyrgyzstan); (4) providing housing and lodging for the large field party at the IVTRAN laboratory outside Bishkek; (5) coordinating a month-long, four-team reconnaissance effort, including field support from geologists familiar with the regional geology to assist with site selection; (6) providing personnel to serve as primary and secondary operators; (7) organizing an enormous flotilla of field transportation, food, and local logistical support at each site.

Data Analysis

The original data recorded in the field were transferred onto floppy disks, either at the end of each 60-hr session, or more frequently for those SSE receivers that lacked the capacity to store more than 40 hours of data. Three copies of all field data were made and verified before leaving Bishkek. We left one copy with Kyrgyzgeodeziya in Bishkek and brought two copies to the US. One copy has been archived at UNAVCO. We will also archive a copy with CDDIS. We will soon send our colleagues in the former Soviet Union tapes with the raw and processed data in RINEX format, plus results of our analysis to date.

Our data analysis procedure has two main steps. In the first step, we broke the rather long (60-hour) sessions into a series of 24-hour (or 12-hour) sessions, organized by GPS day. We analyzed each day of data from all our receivers, along with data from the closest stations in the global tracking network, using the GAMIT software developed at MIT and Scripps. We used daily orbits provided by the Scripps orbit facility as the starting model. The data were cleaned and cycle slips were patched, where possible, either manually or automatically. Integer ambiguities were resolved, where appropriate, using well-known techniques. The output of this stage of the analysis is an estimate of station coordinates and other parameters (e.g., orbit perturbations and atmospheric parameters), along with their covariance matrices, for each day on which observations were made.

In the second step of the analysis, we combined the individual daily solutions into a solution for coordinates and (where appropriate) velocities using the GLOBK software package developed at Smithsonian Astrophysical Observatory and MIT. GLOBK rigorously combines the adjustments of the site coordinates and orbital parameters and their covariance matrices from the individual-day solutions using a Kalman filter. We have experimented with several different strategies for this combination. In the most simple approach, which we call the "mean coordinate" solution, we tightly constrain the orbits to the values determined by the Scripps orbit facility and combine the daily relative coordinates obtained from GAMIT for each base line to estimate mean relative coordinates for each base line. This solution is equivalent to calculating a weighted mean of the GAMIT solutions.

In the second approach, which we call the "local solution," we tightly constrain the satellite orbits and the coordinates of the global tracking network. We simultaneously adjust the coordinates for all of the local sites for an entire experiment, enforcing closure. Because in different experiments, different sites are observed simultaneously, the coordinates estimated with closure enforced differ from those estimated on a base line by base line basis.

In the third approach, which we call the "global" solution, we simultaneously estimate local station coordinates, global station coordinates, and satellite orbits. In areas of the world well covered by the global tracking network (e.g., in California), results obtained using the second and third approaches are nearly identical. As we show later, such is not the case for our network in Central Asia, where the local data have a substantial impact on the estimates of satellite orbits.

We have benefited enormously from a development not anticipated when this project was planned. During the summer, 1993, Thomas Herring at MIT modified the GAMIT software to make more of the processing automatic – a development that has made the analysis of the data much more efficient, decreasing the analyst time required by over an order of magnitude. To test his new algorithms, Herring sought a data set with many of the features that ours offers: numerous simultaneous recordings, a wide range of base line lengths, a range of altitudes, etc. Thus, the combination of the efficacy of his new algorithm with his willingness to help analyze the data allowed him and Bonnie Souter to obtain preliminary results in early September, 1993 – less than a month after Souter returned from the field! Accordingly, we submitted an abstract summarizing preliminary findings to the fall AGU meeting. (Appendix A. Note that the preliminary velocity field presented in the abstract has been superseded by the results discussed below. We also submitted an abstract to the European Geophysical Society Meeting, Appendix B.)

Preliminary Results and Interpretation

The following discussion is based on analysis, largely by Herring and Souter, of data obtained both in 1992 and in 1993. We key this discussion around the figures presented.

The results fall into two broad categories: repeatabilities from session to session, and differences between relative positions of benchmarks in 1992 and 1993 (i. e., apparent velocities of the benchmarks).

(1) Repeatabilities of estimated positions.

Throughout the experiment, we recorded at site KULJ, near the Chinese border, and at POL1, a benchmark on the IVTRAN expedition site. (This site is a few hundred meters from the base site, POLY, used in the GFZ-CIS campaign in 1992. We feared that POLY was too close to a sloping metal roof to be free of multipathing. During our training session, however, we recorded simultaneously at POLY and POL1 to allow us to tie our network to the 1992 GFZ-CIS results.) The 18 "independent" measurements of the relative positions of POL1 and KULJ allow us to assess the variability in GPS-inferred relative positions.

The variations in daily horizontal coordinate estimates of KULJ relative to POL1 are shown in Figure 3a. The origin of the figure is the mean position determined for all 18 sessions. Points in the lower half of the figure correspond to days on which the estimated position of KULJ, relative to POL1, is further to the south than average. The error ellipses show the formal 1-σ error estimates. (One σ corresponds to 39% confidence in 2-D. These formal errors are obtained by multiplying the errors estimated by the software by a factor of 3.2. The errors estimated by the software are based on the fit to the raw phase data, assuming white noise. The increase by an arithmetic factor is a correction for the fact that errors in individual observations are not independent, but are correlated for a time of order several minutes. The particular factor 3.2 is based on error analysis for other GPS campaigns, notably in California; Herring is exploring a more sophisticated scheme for error analysis.) The formal errors vary from day to day, but are typically $\pm$ 5 mm in both N and E. The same daily coordinate estimates are shown in Figure 3b, but with the error ellipses omitted and the GPS day number for each coordinate estimate given.

There is good news and bad news. The relative horizontal coordinates for this > 250 km long base line cluster within a distance from the mean less than 9 mm in the north and 5 mm in the east, with a standard deviation about the mean, consistent with the formal errors, of 4 mm in north and 2 mm in east – the good news! This repeatability suggests that relative position estimates based on only one 12- to 24-hour session would, in general, have a (1-σ) uncertainty of < 5 mm. If the errors were random, the error in determination of the mean would decrease as $n^{-1/2}$. For example, observing for 3 sessions would reduce this by a factor of 1.7, to 3 mm.

Yet the scatter in horizontal coordinate estimates in Figure 3 appears to be bimodal, rather than Gaussian. And, in some cases, measurements on 3 successive days show systematic differences by as much as 5 mm from the average of the 18 sessions – the bad news. As an illustration, we highlight days 197-198-199 and 203-204-205 in Figure 3b. The difference in mean horizontal position between these two 3-day sessions is 11 mm. This behavior suggests that errors are not random and that measurements spanning a period of time as long as 3 days may not always average systematic errors (due to atmospheric conditions?) that are uncorrelated only over longer periods.

The base line between sites MEDE and AZOK was observed for every day of our 1992 campaign, although it was only observed for a single 3-day session in 1993. Figure 4 shows the scatter in horizontal coordinates for MEDE relative to AZOK. Error ellipses are comparable to those in Figure 3a, so we omit them and show GPS day number instead. The scatter in 1992 is about 50% larger than the scatter for KULJ-POL1 in 1993, probably as a result of the weaker global tracking network in 1992. Once again, there are systematic differences in mean coordinates averaged over 3-day sessions. For example, the mean position for days 200-201-202 is about a centimeter to the NW of the mean position for days 204-205-206.

The base line repeated most often in both 1992 and 1993 is CHOL-AZOK. Day-to-day repeatability of relative coordinate estimates is shown in Figure 5. In 1992, we made observations on 7 days, with peak-to-peak scatter of 17 mm in E and 11 mm in N. Two 3-day sessions in 1992 are highlighted by lines connecting the coordinate estimates for each day of each session. In this case, the means for these two 3-day sessions are comparable. In 1993, we observed for more days – 12 – with a comparable peak-to-peak scatter in N and about 50% less scatter in E, again suggesting an improvement in repeatability in 1993. The scatter on this base line in 1993 is comparable to that on the most frequently observed line between KULJ and POL1. Relative positions from some successive days cluster near to one another (e.g., 198-199-200), again suggesting that uncertainties obtained from several successive days might not always be smaller than those obtained for shorter periods.

(2) Coordinate differences between 1992 and 1993

At 12 of the 13 sites occupied in 1992, we obtained at least three 12- to 24-hour sessions in 1993. (The road to the 13th was destroyed during heavy rains.) In Figure 6, we show the daily differences in calculated positions of sites relative to AZOK, expressed as differences from the mean position obtained in 1992 (asterisk). Circles are from observations in 1992, while pluses are for 1993. Again, formal error ellipses are comparable to those shown in Figure 3a and are omitted. This figure shows information equivalent to that in Figures 4 and 5, but for all the repeated sites, in a map format.

There are three features to be noted here.

1. Most scatterings of positions from 1992 and 1993 overlap. Thus, most of the sites show no resolvable displacement between 1992 and 1993. (Scatters are generally less in 1993 than in 1992 due to improvements in the global tracking network.)

2. One of the longest north-south base lines is for stations CHOL and AZOK. This pair of sites has the virtue of being measured during 7 days in 1992 and 12 days in 1993. Consequently, considerably more data contribute to the apparent displacement than between any other pair of sites, so this pair of sites shows the most robustly determined apparent displacement. As can be seen at a larger scale in Figure 5, although there is some overlap, all but one of the estimated positions of CHOL in 1993 lie to the north (closer to AZOK) and to the east of the mean position estimated in 1992. Thus, we think that these data indicate a northeastward displacement of ~ 7 mm, with shortening of ~ 5 mm. Such convergence is consistent with the geologic structure and the seismicity of the region.

3. The largest apparent displacement is between two sites located on relatively stable portions of the Kazakh platform: KURD and AZOK. Taken at face value, the difference suggests that KURD moved east ~ 15 mm with respect to AZOK in the interval between the measurements. The difference between relative positions of 15 mm is large, but it is smaller than the total range observed for the shorter line between MEDE and AZOK in 1992 (see, e.g., days 196-197-198 in Figure 4). With only 3 days of observation each year, we cannot reject the hypothesis that the apparent displacement is an unfortunate artifact. We expect there to be at most very slow (< 1 mm/a) relative movement between these sites, for both sites seem to lie on the relatively stable Kazakh platform. We are in the process of studying this apparent anomaly. Fortunately, KURD is part of the GFZ-CIS regional network observed in 1992. We have agreed with Christof Reigber to compare solutions in the near future.

We have performed the three types of analyses using GLOBK described above to estimate apparent velocities more formally: (1) Differences of the mean relative coordinates from weighted averages of individual daily sessions; (2) Differences between coordinates for each year from a combination of local data that enforces closure among sites not observed simultaneously, and does not adjust satellite orbits; and (3) Differences between coordinates for each year from a "global" combination of local and global tracking data, including adjustment of satellite orbits. While there are a number of features in the coordinate differences that are similar among all three analyses, there are also a number of differences that are large enough to be noticeable (Figures 7-9). Comparing these solutions gives us insight into the reliability of our results and ideas about how to improve them.

Figure 7 shows the "Repeatability Velocity Field" of our repeat sites, relative to AZOK, a site observed in common with all of these sites both years. The vectors show the displacements calculated from the differences in weighted means, for 1993 and 1992, of the relative coordinates shown in Figure 6. Two types of error ellipses are shown, both at 95% confidence level (2.5 σ). The heavy lines show the uncertainties propagated through from the statistical fit to the phase data, while the light lines show the uncertainties calculated from the scatter of the relative coordinate estimates. For CHOL, the two error estimates are quite similar, whereas for MEDE, the scatter in the daily coordinate estimates is substantially greater than expected from the formal errors.

Figure 8, the "local" velocity field, shows the results of using GLOBK to enforce closure among all local sites simultaneously, but not using the local data to change the "global" parameters (satellite orbits and tracking station coordinates). For most sites, the velocities are nearly the same as before, but there are some exceptions. Consider, for example, site CHRN, which now has a significantly lower westward component of its velocity relative to AZOK. In 1992, CHRN was observed simultaneously with site MEDE (but not CHOL) on days 204-205-206 – days on which the relative position estimated for MEDE relative to AZOK was ~ 5 mm to the east of the12-day mean (see Figure 4). The result of GLOBK forcing MEDE to a single estimated position (for all 12 days observed) to the west of its estimate for the days that MEDE was observed with CHRN is to displace the estimate of CHRN (in 1992) to the west as well, decreasing its apparent westward displacement in 1993.

Figure 9, the "global velocity field, shows primarily the effects of allowing the local data to affect the estimate of global orbits. The main effect is slightly larger westward velocities in the western half of the network. It is mainly the 1992 position estimates that are affected, suggesting again that the orbital control was better in 1993 than in 1992.

There are two fundamental problems that we are investigating which may explain the differences between the different types of analyses: (1) appropriate modeling of the error spectrum of the GPS carrier phase noise; and (2) the treatment of the satellite orbits over the Central Asia region. The first of these areas is a general problem in GPS analyses. The error model in our current GAMIT analyses assumes that the carrier phase noise can be modeled with a Gaussian white noise process, with the same standard deviation for all stations and satellites. Examination of post-fit carrier phase residuals shows that such a model is not representative of the true error spectrum because the postfit residuals show correlation times that are variable between stations and satellites. A consequence of this inadequate error model is that the standard deviations of the estimates of station coordinates from our analyses appear to underestimated by a large factor. Our estimate of this factor for the Central Asia data based on the χ^2 per degree of freedom from the GLOBK combination of the local and global tracking data is ~3.2. However, this figure is a composite average over all stations and the two campaigns, and is likely to be an overestimate for some stations and underestimate for other stations. One of our students is now analyzing the spectra and correlation functions of the post-fit carrier phase residuals so that a better error model can be developed.

The other area we are investigating is the nature of orbital errors over Central Asia. There are no global tracking sites in this region and we suspect that some the differences between the combined global and local data analysis (Fig. 9) and the local data only analyses (Figure 8), are due to errors in the satellite orbits over Central Asia when only global tracking data are used to determine the orbits. In the combined global and local analyses, the local data contribute to the orbit determination. Based on the increments in the χ^2 per degree of freedom when the local data are added to the global data, there does appear to be significant orbital information contributed by the local data. As part of the general upgrades to the GAMIT package to better represent noise processes in GPS data and to better model the physical system (i.e., effects such as antenna phase center variations, ocean loading and improved solid Earth modeling), we expect to gain a much better understanding and accounting for orbital errors over remote areas.

In summary, we can now determine relative displacements between sites hundreds of kilometers apart quickly, efficiently, and precisely. Formal errors are ~ ± 5 mm. Observing for many sessions decreases the uncertainties, but not as rapidly as it would if the error spectrum were white. We are working on ways to improve the analysis. In its current state, we should be able to resolve velocities at the level of a few mm/yr after our next major survey in 1995.

FUTURE WORK

Our future work until we remeasure the network in 1995 includes (1) further analysis of existing GPS data, (2) training of our (former) Soviet colleagues and preparing for the next campaign, and (3) additional geological, geomorphological, and seismological studies that are basic to an interpretation of the GPS results when we have the new data.

(1) As should be clear from the brief summary above, further analysis of the existing data and development of improved software is ongoing. We are fortunate to have

acquired as a collaborator Tom Herring, who is fascinated by our unique data set. This shows the serendipity possible through close cooperation between those who undertake the massive logistics needed to collect the data and those who develop the sophisticated software and expertise needed to process it.

(2) Through a special NSF initiative to help provide infrastructure support for scientific organizations in the former Soviet Union, we are planning to establish a data processing facility in Bishkek during the early months of 1994, most likely based at Kyrgyzgeodeziya. A second facility will be established in collaboration with the IRIS data processing center at the IVTRAN laboratory near Bishkek. We plan to conduct a formal training program on GPS data processing for our Russian, Kyrgyz, and Kazakh counterparts. The current plans include a two-week short course, conducted during early summer, 1994, at the IVTRAN facility, by Thomas Herring of MIT.

We are currently planning to repeat measurements of the 86-station Tien Shan GPS network in mid-1995. Our counterparts in Russia, Kyrgyzstan, and Kazakhstan are actively pursuing the necessary formalities and seeking funds to support this effort. We are also exploring possibilities of joint observations, with Chinese colleagues, that would permit us to tie the Tien Shan network to the Tarim Basin to the south. During the next field campaign, we also hope to make ties with other regional networks operating in Nepal, India, and China in order to provide regional tectonic measurements of the India-Eurasia plate motion.

(3) At the same time, several of us are independently pursuing related projects on structural geology, neotectonics, seismicity, and lithospheric structure of the Tien Shan. These include: (a) a regional project to examine active geologic structures and seismicity associated with the deformed sedimentary basins in the Tien Shan (M. W. Hamburger and S. Ghose, Indiana University; through support from the USGS, and a proposal to NSF pending review); (b) a detailed study of the surface faulting and aftershocks associated with the 1992 Suusamyr earthquake (R. Mellors, S. Ghose, M. W. Hamburger, Indiana University; through support from the USGS and IRIS); (c) ongoing seismotectonic studies using the IRIS broadband seismic network extending across the northern Tien Shan mountain front in Kyrgyzstan and Kazakhstan (R. Mellors, M. W. Hamburger, G. Pavlis, Indiana University; through support from IRIS); (d) ongoing seismotectonic and earthquake prediction studies in the Pamir-Tien Shan region (M. W. Hamburger, G. Pavlis, Indiana University); (e) a synthesis of large earthquakes and geological constraints on rates of active deformation in the Tien Shan, a study begun with support from a previous NASA grant (P. Molnar, MIT); and (f) a summary of Quaternary faulting along the Talaso-Ferghana fault, which will report results of field investigations of V. S. Burtman, S. F. Skobelev, and P. Molnar in 1991 (P. Molnar, MIT). In addition, we are in the

planning stages of a multidisciplinary project that will include geological, geomorphic, geodetic, seismological, and magnetotelluric investigations in order to examine the deep structure and lithospheric dynamics of the Tien Shan. This will begin with a workshop and field trip in the Kyrgyz Tien Shan during the summer of 1994. Support from the Continental Dynamics project of NSF will be sought.

TABLES

Table 1. List of participants and participating organizations.

Table 2. Site numbers, names, 4-character ID's, the GPS days observed in 1993, and coordinates of our network.

FIGURES

Figure 1. Map of central and eastern Asia showing topographic and structural setting of the Tien Shan (from J.-C. Thomas, Ph.D. thesis, Univ. of Rennes, 1993).

Figure 2. Map showing both our geodetic network (1992: shaded circles; 1993: black triangles) and the GFZ-CIS regional network(open circles). (Note that the 3 westernmost shaded circles are also part of the GFZ-CIS network.)

Figure 3. Repeatability of relative horizontal coordinate estimates for the most frequently observed base line in 1993, KULJ-POL1. (a) 1- σ error ellipses (39% confidence level in 2-D). (b) Same coordinate estimates, with GPS day numbers indicated. The 3-day sessions discussed in the text are indicated by the lines connecting day numbers.

Figure 4. Repeatability of relative horizontal coordinate estimates for the most frequently observed base line in 1992, MEDE-AZOK, with GPS day numbers indicated.

Figure 5. Repeatability of relative horizontal coordinate estimates for CHOL-AZOK. Relative coordinates are given for seven days in 1992 and 13 days in 1993, with GPS day numbers indicated. The 3-day sessions discussed in the text are indicated by the lines connecting day numbers.

Figure 6. Differences in horizontal coordinates between 1993 and 1992 for each site, relative to AZOK, plotted in map view, relative to the mean coordinates determined for 1992.

Figure 7. Differences in coordinates between the 1993 and 1992 Central Asia campaigns, expressed as velocities, determined from the differences in the mean coordinates from single session analysis in each of the campaigns. The thick-lined error ellipses are 95% confidence ellipses based on the statistical uncertainties of the weighted means of the coordinates from each campaign multiplied by 3.2 (see text). The thin- lined error ellipses are the 95% confidence intervals derived from the weighted root mean square (WRMS) scatter of the coordinate repeatabilities for each of the stations separately.

Figure 8. Differences in coordinates between the 1993 and 1992 Central Asia campaigns, expressed as velocities, determined from the differences of the coordinates from combined local data in each campaign. The error ellipses are 95% confidence with the statistical uncertainties multiplied by 3.2 (see text).

Figure 9. Differences in coordinates between the 1993 and 1992 Central Asia campaigns, expressed as velocities, determined from the determined form the combined local and global-tracking data. The error ellipses are 95% confidence with the statistical uncertainties multiplied by 3.2 (see text).

Table 1. Participants In 1993 GPS Field Experiment

Scientist	Institution
S. Ghose	Indiana University
M. Hamburger	Indiana University
R. Mellors	Indiana University
X. Song	Indiana University
B. Hager	Massachusetts Institute of Technology
P. Molnar	Massachusetts Institute of Technology
S. Panasyuk	Massachusetts Institute of Technology
R. Reilinger	Massachusetts Institute of Technology
B. Souter	Massachusetts Institute of Technology
B. O'Neill	UNAVCO Consortium
B. Bakka	IVTRAN (Institute of High Temperatures, Russian Academy of Sciences)
V. Bocharov	IVTRAN
L. Bogomolov	IVTRAN
V. Bragin	IVTRAN
R. Shamiev	IVTRAN
G. Schelochkov	IVTRAN
S. Sultanov	IVTRAN
V. Sychov	IVTRAN
Yu. Trapeznikov	IVTRAN
P. Yeremeev	IVTRAN
B. Zaitsev	IVTRAN
A. Zubovich	IVTRAN
S. Baranova	Institute of Physics of the Earth, Russian Academy of Sciences
O. Galaganov	Institute of Physics of the Earth, Russian Academy of Sciences
V. Gulin	Institute of Physics of the Earth, Russian Academy of Sciences
V. Perederin	Institute of Physics of the Earth, Russian Academy of Sciences
M. Prilepin	Institute of Physics of the Earth, Russian Academy of Sciences
Yu. Kopnichev	Talgar Seismological Expedition, IPE
I. Sokolova	Talgar Seismological Expedition, IPE
V. Chernyavsky	Kyrgyz State Agency for Geodesy and Cartography
V. Kuzmechenok	Kyrgyz State Agency for Geodesy and Cartography
M. Mingazhev	Kyrgyz State Agency for Geodesy and Cartography
V. Obidenko	Kyrgyz State Agency for Geodesy and Cartography
R. Salo	Kyrgyz State Agency for Geodesy and Cartography
V. Sannikov	Kyrgyz State Agency for Geodesy and Cartography
V. Smirnov	Kyrgyz State Agency for Geodesy and Cartography
V. Tsurkov	Kyrgyz State Agency for Geodesy and Cartography
G. Yermakov	Kyrgyz State Agency for Geodesy and Cartography
K. Abdrakhmatov	Kyrgyz Institute of Seismology
I. Sadybakasov	Kyrgyz Institute of Geology
I. Borodin	Kazakh Central Administration for Geodesy and Cartography
V. Ostroumov	Kazakh Central Administration for Geodesy and Cartography
M. Ostroumov	Kazakh Central Administration for Geodesy and Cartography
V. Kozlov	Kazakh Central Administration for Geodesy and Cartography
A. Markin	Kazakh Central Administration for Geodesy and Cartography
L. Zhalilov	Kazakh Central Administration for Geodesy and Cartography
V. Peredero	Kazakh Institute of Seismology
S. Aldazhanov	Kazakh Landslide Control Agency
A. Slezarchuk	Kazakh Landslide Control Agency
I. Tkachenko	Kazakh Landslide Control Agency

GPS93SITES

STATION NUMBER	STATION ID	STATION NAME	JULIAN DAY 189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	LATITUDE (DEGREES N)	LONGITUDE (DEGREES E)	ELEVATION (M)
12	KKTL	KOKTAL													■	■	■	■	■	43.271	70.222	690
15	ALAB	ALABUKA														■	■			41.362	71.460	1180
17	CHAT	CHATKAL																■	■	42.014	71.721	2970
19	UZUN	UZUNAHMAT																■	■	41.980	72.498	1220
20	KKAU	KARASU														■	■	■	■	41.695	72.894	1240
21	KAKK	KARAKSHTAK													■	■	■			42.806	72.904	1040
25	SRBL	SARYBULAK							■	■	■									42.786	78.307	1860
27	CHUO	CHU										■	■	■						43.423	74.002	580
32	KURD	KURDAI										■	■	■						43.379	75.086	580
33	ADAR	AIDARLY										■	■	■						44.132	75.525	620
35	ALBL	ALABEL							■	■	■									42.313	76.167	1640
36	KULJ	KULDJABASH	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	40.816	76.298	3240
37	MAYA	MAIA							■	■	■									43.155	76.478	1070
101	KAZY	KAZYKURT																■	■	42.036	69.824	1254
102	UGAM	UGAMTAU																■	■	42.280	70.254	1598
103	BRLD	BOROLDAYTAU													■	■	■			42.569	70.520	1298
104	KUMB	KUMBEL																■	■	41.669	70.600	1778
105	SAND	SANDALASH																■	■	41.697	70.881	1541
106	KTAU	KARATAU													■	■	■			42.783	70.940	1076
107	TERK	TEREKSAI																■	■	41.539	71.146	1666
108	KBUR	KARABURA																■	■	42.202	71.579	3295
109	SHIL	SHIL-BELI										■	■	■	■	■	■	■	■	42.454	71.532	1254
110	JAMB	JAMBYL																■	■	42.908	71.526	880
111	BOZB	BOZBUTAU														■	■			41.495	71.792	1400
112	URMA	UHRMARAL																■	■	42.354	71.958	1385
113	ABDU	ABDU-KALYK														■	■			41.784	72.050	1110
114	SHAM	SHAMSI										■	■	■						42.622	75.397	1481
115	AKJL	AKJOL														■	■			41.557	72.145	780
116	KENK	KEN-KOL																■	■	42.593	72.367	1506
117	CHYK	CHYCHKAN														■	■			41.966	72.875	1089
118	SKAR	SHUM-KAR													■	■	■			42.410	72.920	1913
119	OTMK	OTMEK																■	■	42.235	73.201	2836
120	TORK	TORKENT																	■	41.895	73.159	1356
121	SUUS	SUUSAMYR													■	■	■			42.206	73.555	2387
122	KHAI	KHANTAU										■	■	■	■	■	■			44.380	73.672	479
123	KRYS	KRYSHA																		42.876	74.594	736
124	MOLD	MOLDOTAU										■	■	■						41.669	75.038	3200
125	KKOL	KARAKOL													■	■	■			42.257	75.146	2726
126	KYZA	KYZART										■	■	■						42.092	75.135	2621
127	SONG	SONG-KUL							■	■	■									41.914	75.423	3510
128	KULA	KULANAK							■	■	■									41.358	75.569	2190
129	KKOY	KARAKOYUN				■	■	■												41.018	75.550	2400
130	JUAN	JUANARYK										■	■	■						42.105	75.645	1950
131	DEGE	DEGRES							■	■	■									43.245	75.766	1230
132	TOKO	ORTO-TOKOI										■	■	■						42.355	75.837	2130
133	AKSA	AKSAI	■	■	■															40.717	75.967	3390
134	KAIN	KAINDY				■	■	■												41.173	76.101	2405
135	KEKE	KECHI-KEMIN										■	■	■						42.758	76.057	1721
136	RYBA	RYBACHE										■	■	■						42.523	76.102	2160
137	NARY	NARYN							■	■	■									41.445	76.255	2280
138	KKDJ	KARAKUDJUR				■	■	■												41.902	76.205	2730
139	TEGE	TEGEREK							■	■	■									42.137	76.594	2130
140	KURT	KURTY							■	■	■									43.894	76.339	660
141	ATAK	ATA-KURGAN				■	■	■												43.337	76.869	683
142	KARG	KARAGOMAN	■	■	■															41.733	76.776	2707
144	MEDE	MEDEO				■	■	■												43.179	77.017	1343
145	CHOL	CHOLPONATA	■	■	■	■	■	■	■	■	■	■	■	■						42.718	77.074	2469
146	AZOK	AZOK	■	■	■	■	■	■	■	■	■	■	■	■						43.897	77.114	432
147	ISYK	ISSYK							■	■	■									43.261	77.490	1737
148	ANAN	ANAN'EVO							■	■	■									42.792	77.603	1840
149	CHAK	CHAKYR-KORUM				■	■	■												41.527	77.739	3190
150	ARAB	ARABELSU	■	■	■															41.860	77.750	3751
151	ALTY	ALTYN EMEL							■	■	■									43.908	77.763	564
152	CHLZ	CHUL-ZHOTA				■	■	■												43.267	77.845	2716
153	KURA	KURAM				■	■	■												43.483	78.161	992
154	ORGO	ORGOCHOR				■	■	■												42.440	77.918	1669
155	JETY	JETTY OGUZ	■	■	■															42.297	78.275	2276
156	ISHT	ISHTYK	■	■	■	■	■	■	■	■	■									41.601	78.210	3497
157	DALA	DAL ASHYK	■	■	■															43.137	78.457	1574
158	TYUP	TYUP		■	■															42.632	78.509	1739
159	KOKP	KOKPE	■	■	■															43.452	78.645	1154
161	AKSH	AKSHYRAK				■	■	■												41.795	78.542	3443
162	KNSU	KENSU	■	■	■															43.024	78.825	1729
163	TUAK	TURGEN AKSU	■	■	■															42.415	78.948	2779
164	CHRN	CHARYN	■	■	■															43.271	78.975	1038
165	SASH	SANTASH							■	■	■									42.751	78.972	1963
166	INYL	INYLCHEK				■	■	■												42.016	79.071	2556
167	KOYL	KOYLYU				■	■	■												42.166	79.092	2718
168	KRLT	KARALATASH	■	■	■															41.123	76.434	3296
169	RSRB	REKA SARYBULAK										■	■	■						41.697	75.732	2421
170	RSON	REKA SONGKEL										■	■	■						41.760	75.370	3005
171	TUAS	TUASHU													■	■	■			42.320	73.824	2921
172	TOSI	TOSSOR	■	■	■															42.176	77.312	1663
173	TURG	TURGEN				■	■	■												43.315	77.642	1219
174	POLI	POLYGON BISHKEK	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	42.678	74.693	1694

Table 2

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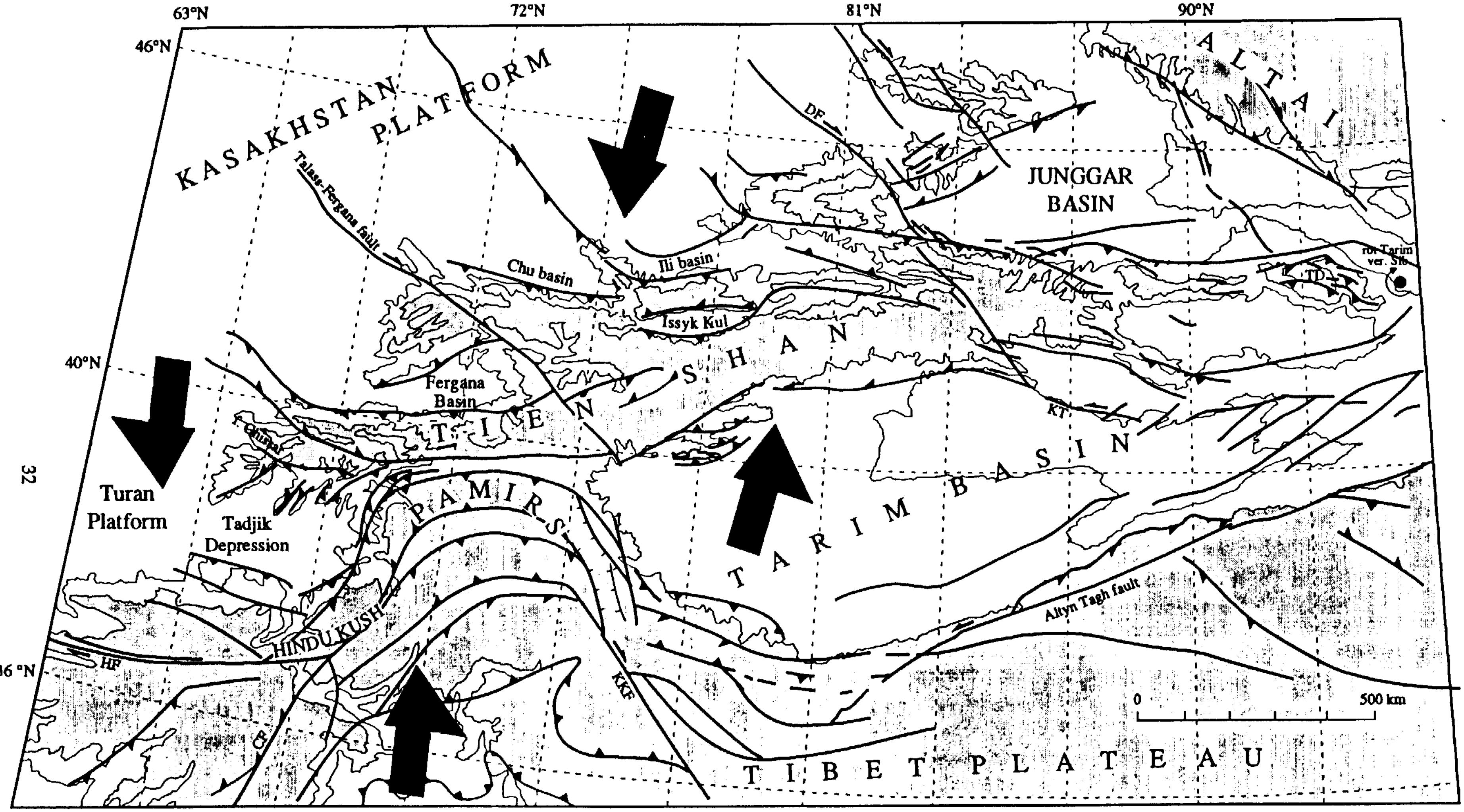

63°N
72°N
81°N
90°N
46°N
40°N
36 °N
KASAKHSTAN PLATFORM
ALTAI
JUNGGAR BASIN
DF
Talass-Fergana fault
Chu basin
Ili basin
Issyk Kul
Fergana Basin
TIEN SHAN
TARIM BASIN
KT
TD
Turan Platform
Tadjik Depression
PAMIRS
HINDU KUSH
HF
CF
KKF
Altyn Tagh fault
TIBET PLATEAU
0
500 km

Figure 1

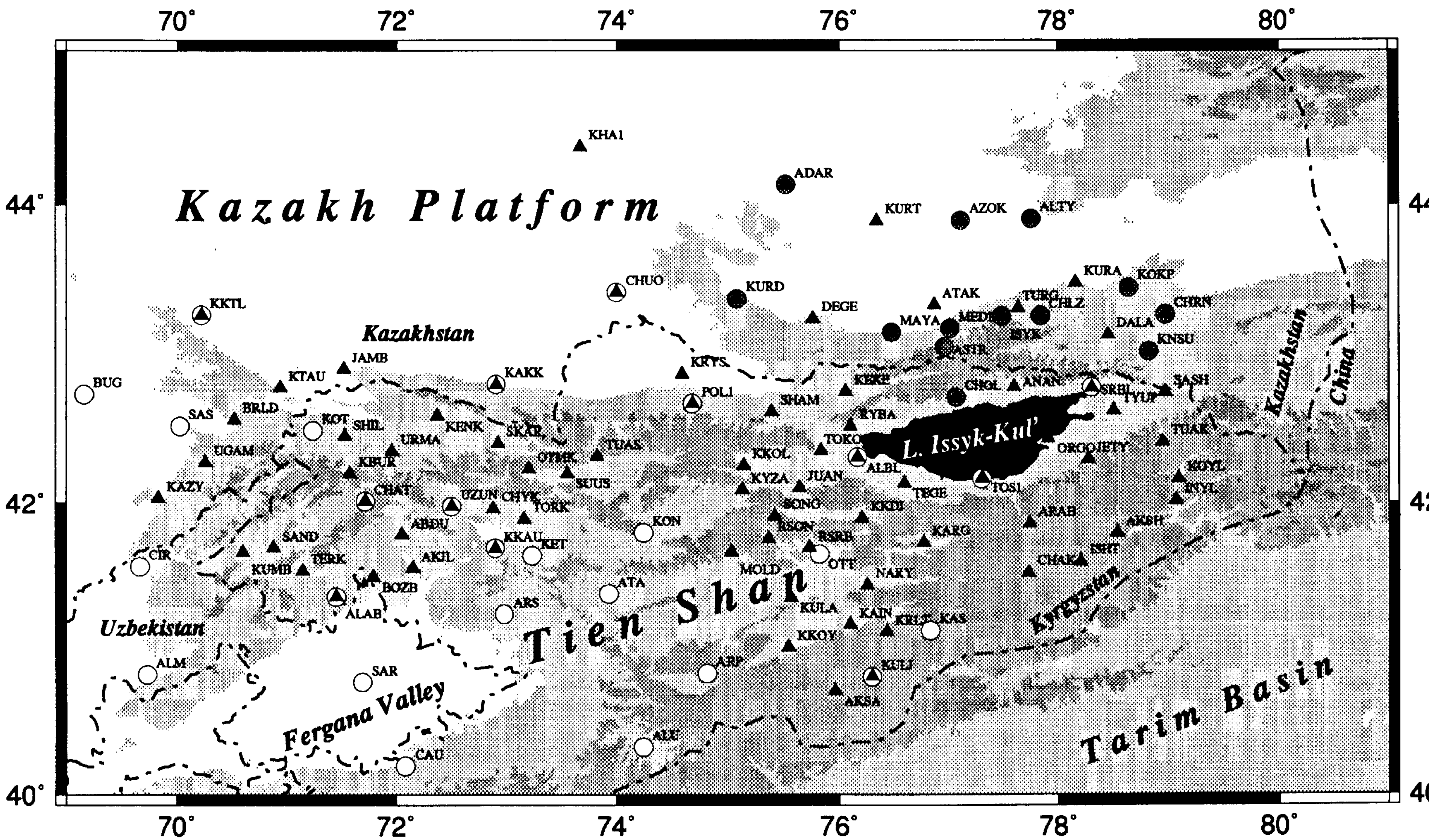
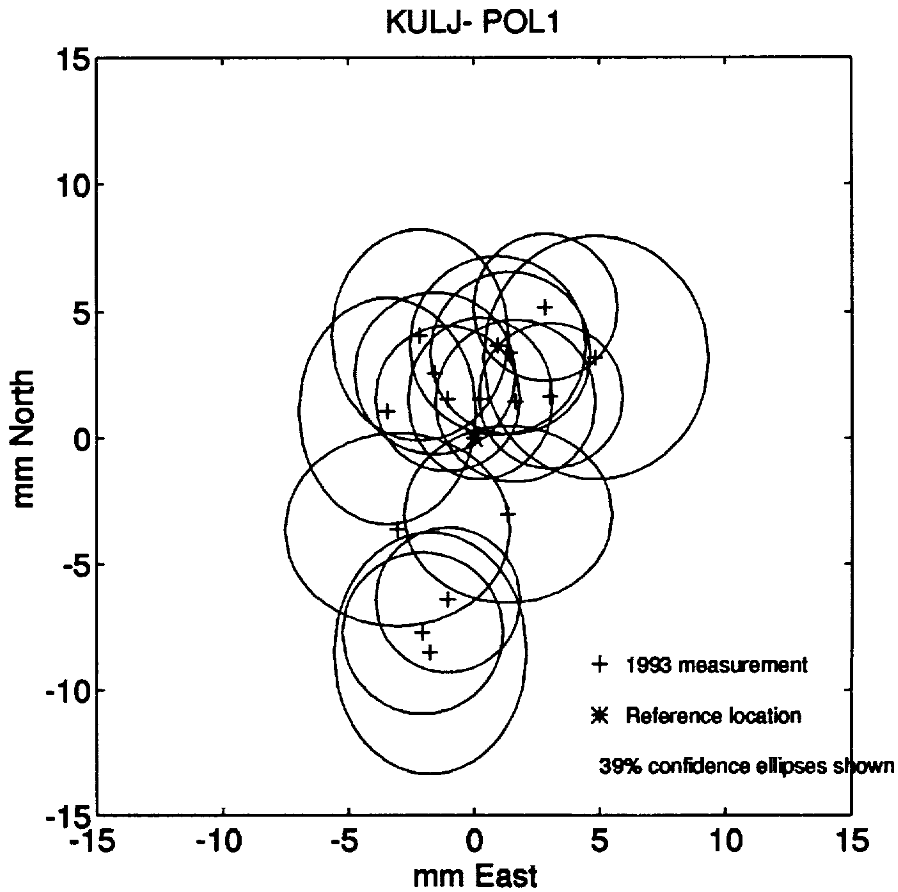
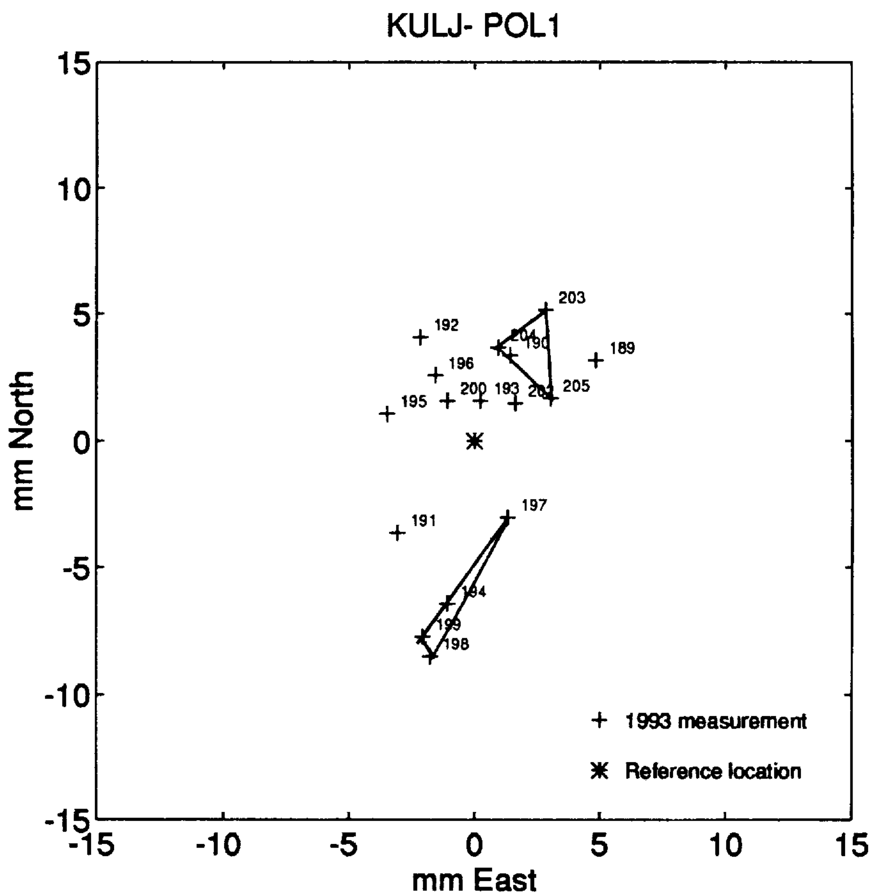

Kazakh Platform
Kazakhstan
Uzbekistan
Kyrgyzstan
China
Tien Shan
Tarim Basin
Fergana Valley
L. Issyk-Kul'
70°
72°
74°
76°
78°
80°
40°
42°
44°

Figure 2



KULJ- POL1
15
10
5
0
-5
-10
-15
-15
-10
-5
0
5
10
15
mm North
mm East
+ 1993 measurement
✳ Reference location
39% confidence ellipses shown

Figure 3a



KULJ- POL1
15
10
5
0
-5
-10
-15
-15
-10
-5
0
5
10
15
mm North
mm East
203
192
204
190
189
196
200
193
201
205
195
191
197
194
199
198
1993 measurement
Reference location

Figure 3b

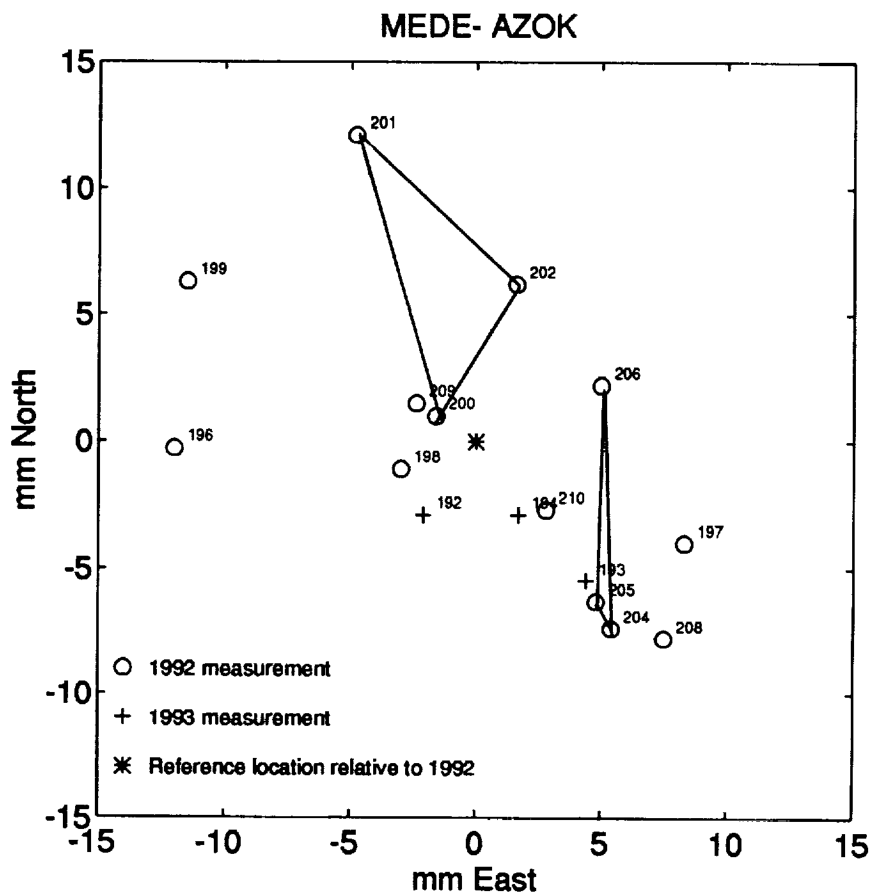

MEDE- AZOK
mm North
mm East
15
10
5
0
-5
-10
-15
-15
-10
-5
0
5
10
15
201
202
199
206
200
196
198
192
210
197
205
204
208
1992 measurement
1993 measurement
Reference location relative to 1992

Figure 4

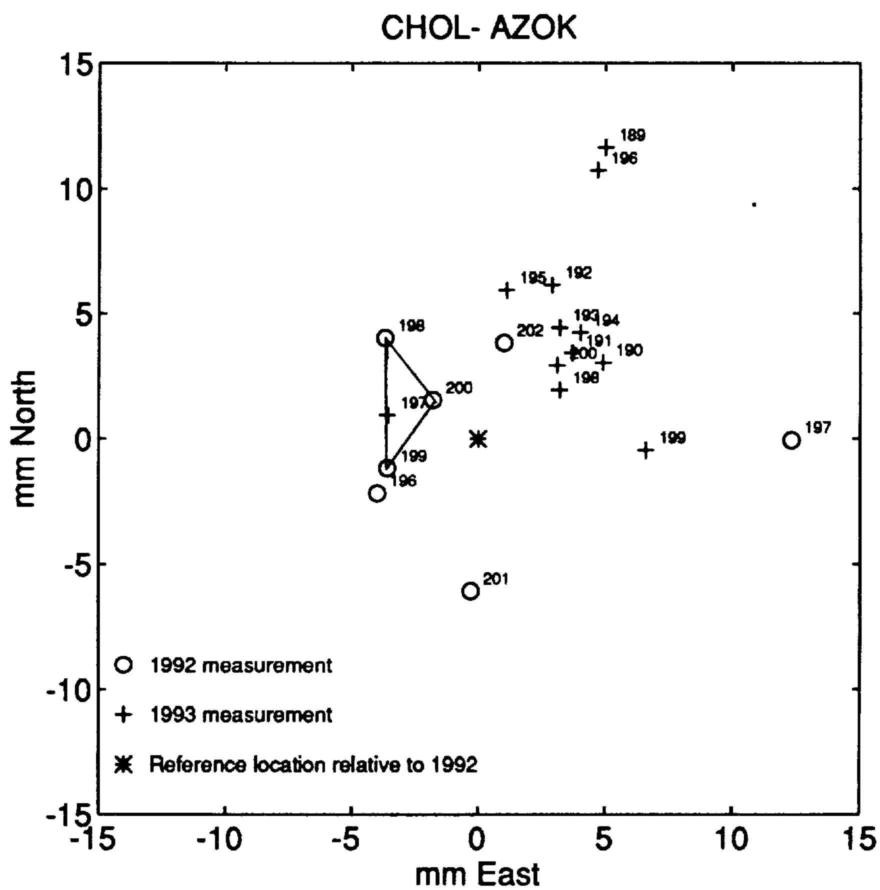

CHOL- AZOK
15
10
5
0
-5
-10
-15
mm North
-15
-10
-5
0
5
10
15
mm East
189
196
195
192
193
194
191
200
190
198
199
198
200
197
199
196
202
197
201
1992 measurement
1993 measurement
Reference location relative to 1992

Figure 5

1992 and 1993 Daily Positions

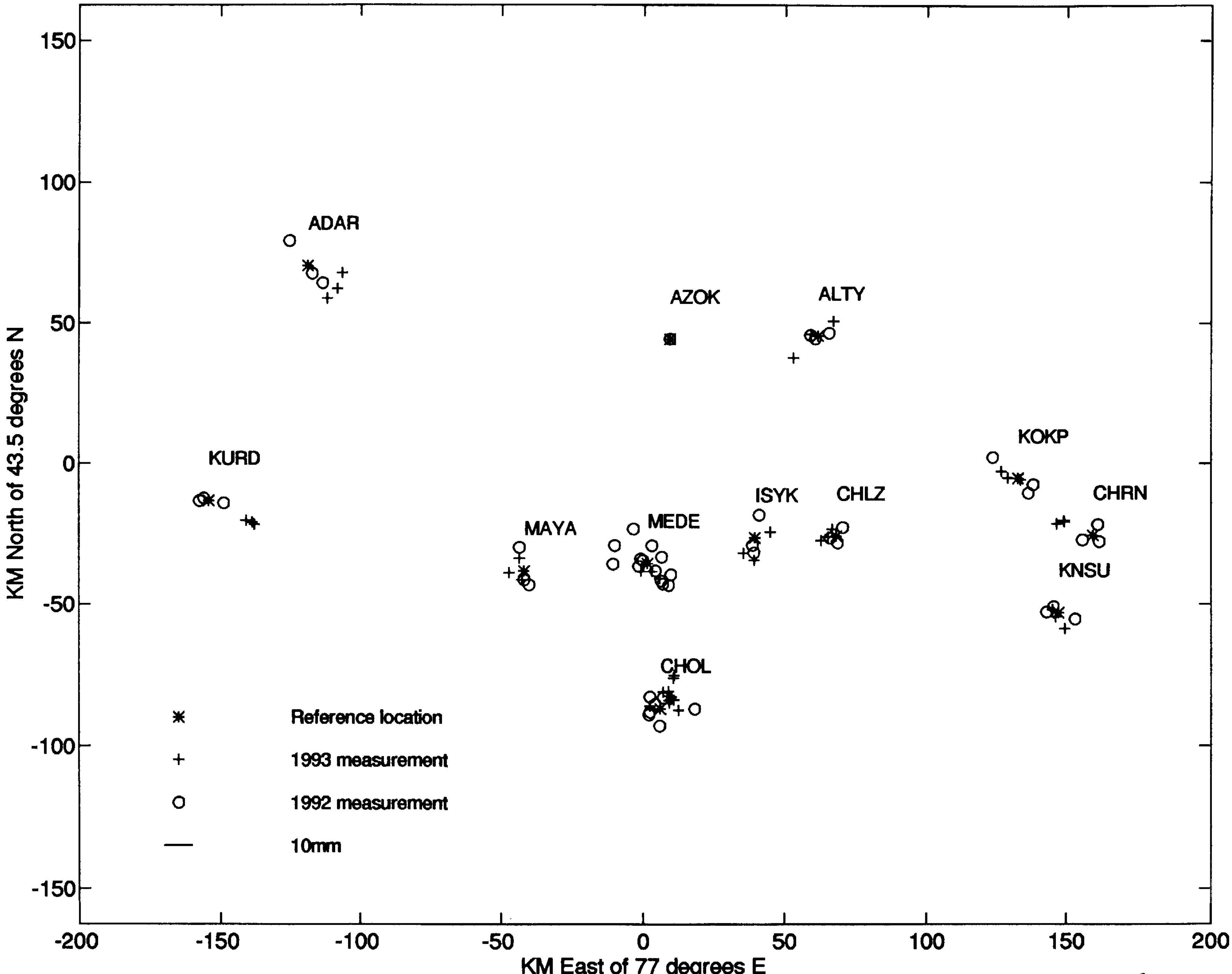
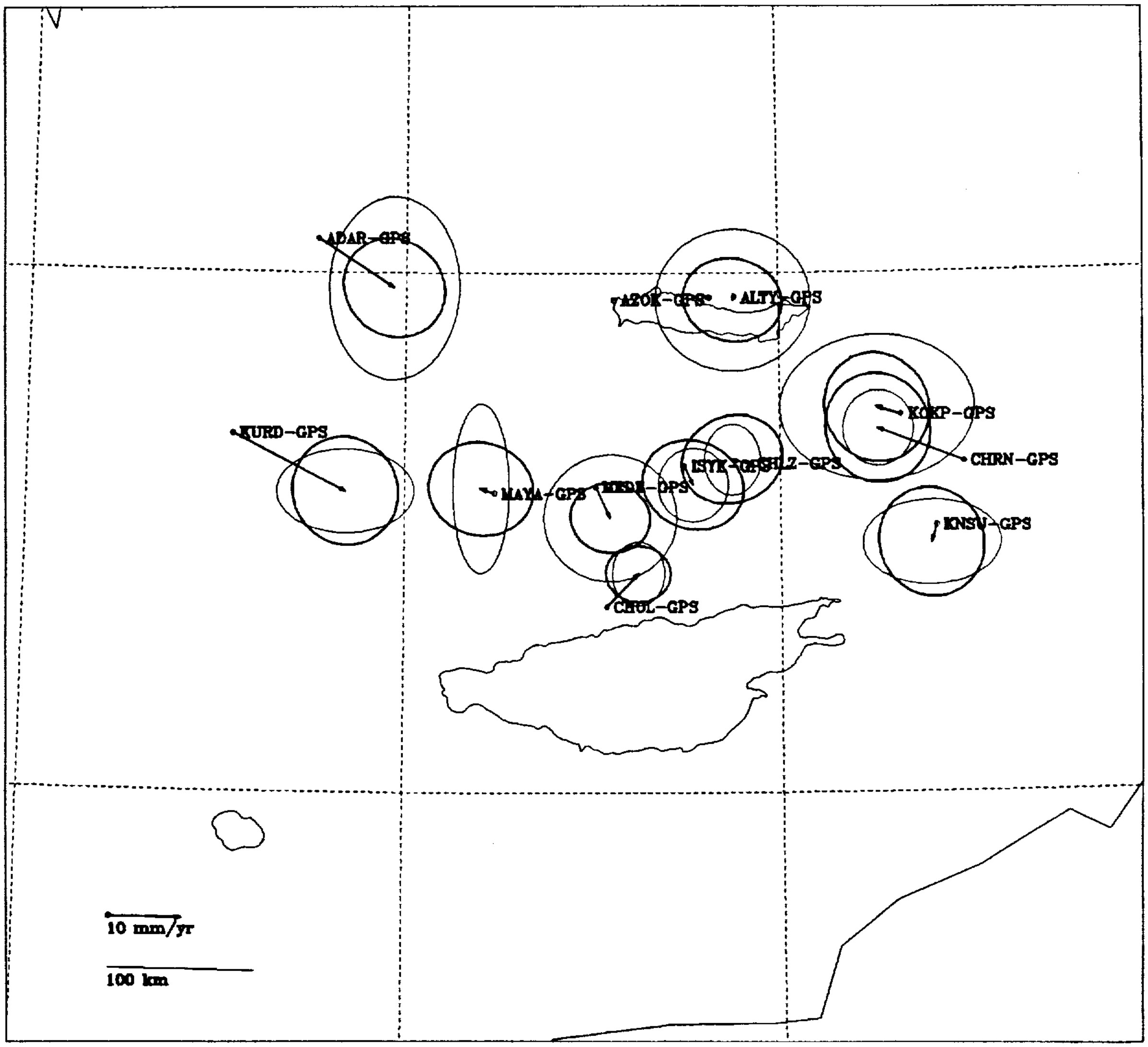


Figure 6

Repeatability Velocity Field

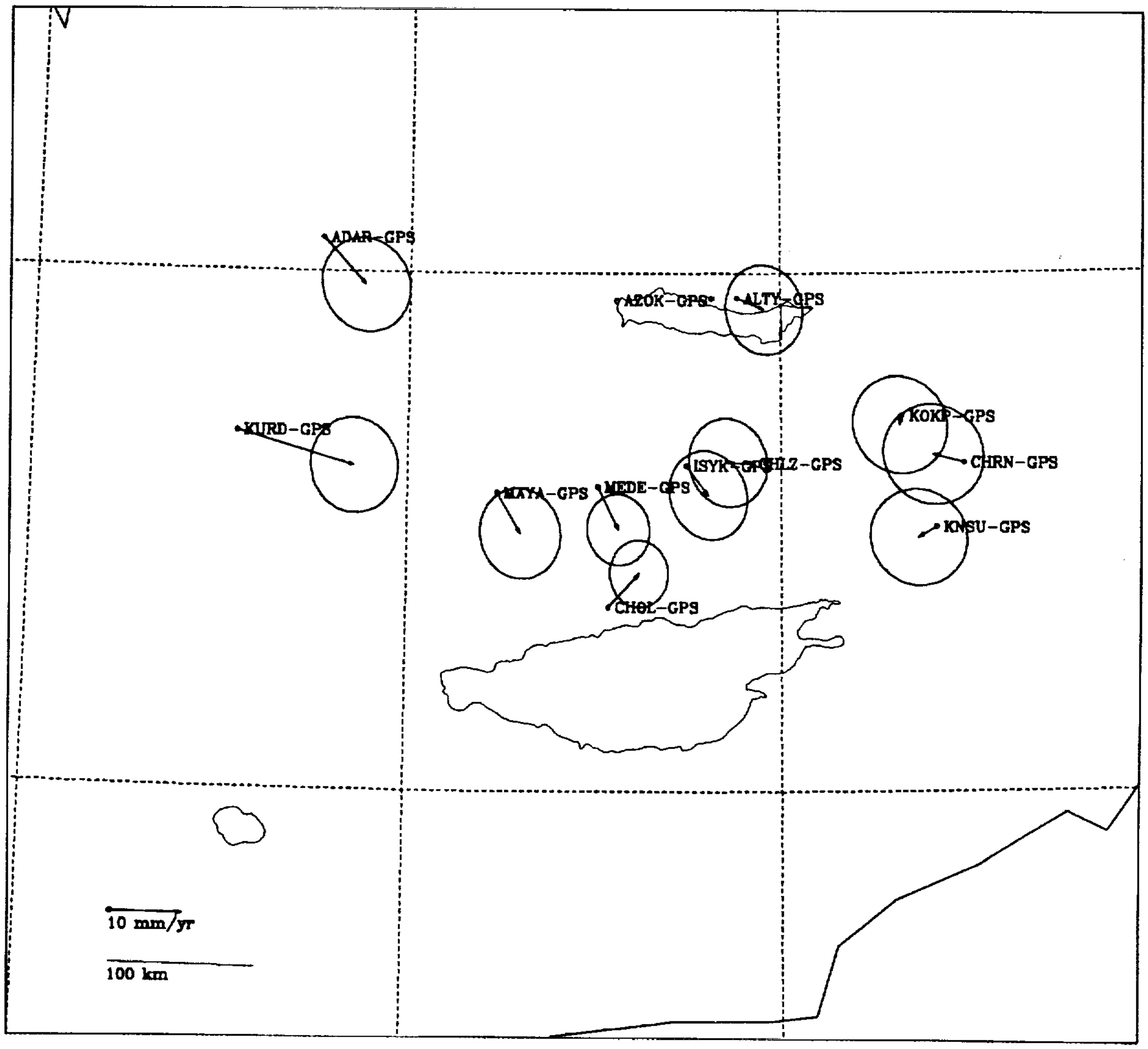


Central Asia Velocity Field

95 per cent confidence, NRMS rescaling

Figure 7

LOCAL Velocity Field

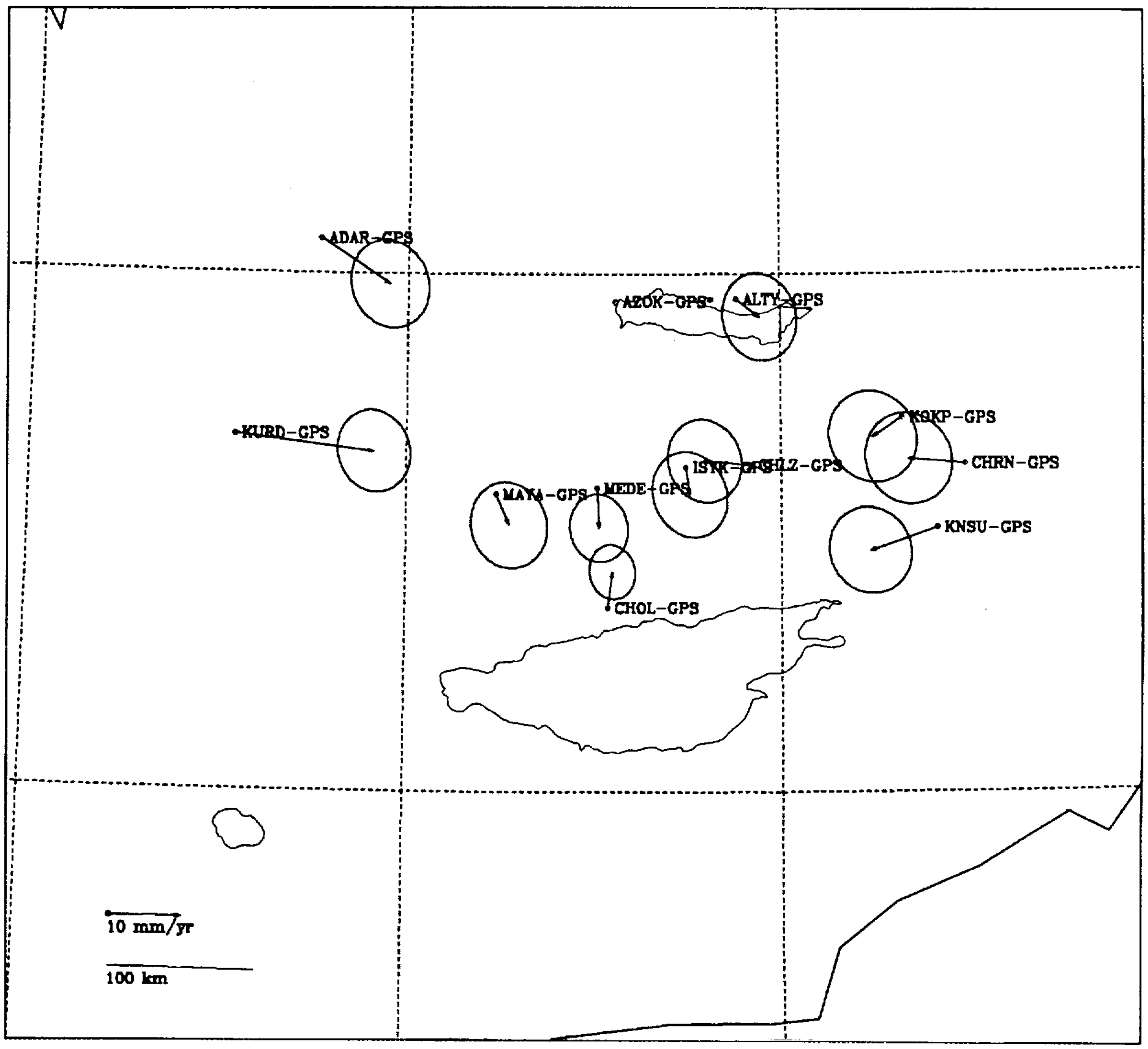


Central Asia Velocity Field

95 per cent confidence, 3.2 rescaling

Figure 8

GLOBAL Velocity Field



Central Asia Velocity Field

95 per cent confidence, 3.2 rescaling

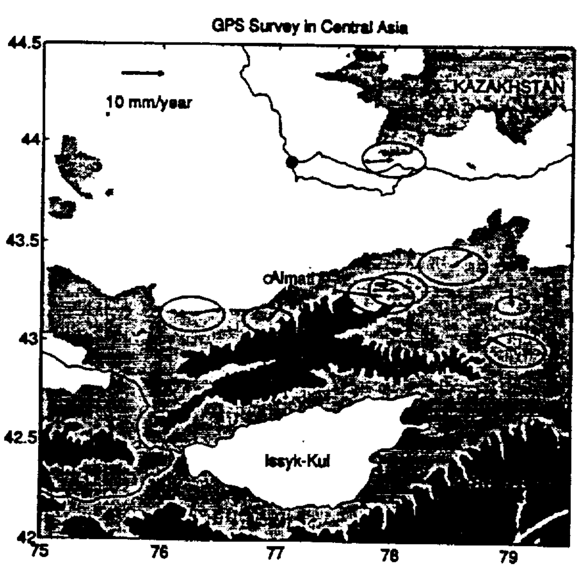
Figure 9

Appendix A

GPS Constraints on Shortening across the Northern Tien Shan of Kazakhstan and Kyrgyzstan

B J Souter (Dept. of Earth, Atmospheric, and Planetary Sciences, M.I.T., Cambridge, MA 02139; 617-253-8872; Internet souter@airy.mit.edu)
Y A Trapeznikov[1], V E Tsurkov[2], T M vanDam[3], K Abdrakhmatov[4], S A Aldajanov[5], V N Gulin[6], B H Hager[3], M W Hamburger[7], T A Herring[3], V A Kuzmichenok[2], V I Makarov[8], P Molnar[6], J Normandeau[9], B J O'Neill[9], V Z Ostroumov[11], S V Panasyuk[3], M T Prilepin[6], R E Reilinger[3], I S Sadybakasov[10], N A Shcherbakov[11], X D Song[7] ([1]IVTRAN, Bishkek, Kyrgyzstan; [2]Kyrgyzgeodesia, Bishkek, Kyrgyzstan; [3]Dept. of Earth, Atmospheric, and Planetary Sciences, M.I.T., Cambridge, MA; [4]Kyrgyz Inst. Seism., Bishkek, Kyrgyzstan; [5]Kazselezacshita, Almati, Kazakhstan; [6]Inst. of Physics of the Earth, Russian Acad. Sci., Moscow, Russia; [7]Dept of Geological Sciences, Indiana Univ., Bloomington, Indiana; [8]Neotectonics and Remote Sensing Dept., Russian Acad. Sci., Moscow, Russia; [9]UNAVCO, Boulder, CO; [10]Kyrgyz Inst. of Geology, Bishkek, Kyrgyzstan; [11]Kazgeodesia, Almati, Kazakhstan)

GPS measurements in 1992 and 1993 in southeast Kazakhstan and northwest Kyrgyzstan place a bound on the rate of convergence across the Kungey-Alatau range on the northern margin of the Tien Shan. A 13-site network established in 1992 was remeasured in 1993 as part of a larger 85 site network covering an area approximately 300 km by 700 km and including much of the central and western Tien Shan. Both the networks share benchmarks established by a German-Kazakh-Kyrgyz-Russian-Uzbek team in 1992. Our longest north-south baseline, extending across the Kungey-Alatau from north of Issyk Kul to the Ili basin shortened by 8 ± 1 mm. Our longest east-west baseline extended by 7 ± 4 mm. If this shortening over roughly one third of the Tien Shan in this area were applicable to the entire belt, it would imply convergence between the Tarim Basin and the Eurasian plate of 25±4 mm/yr. Our next resurvey of the 85 site network is planned for 1995. Below are shown the velocities of 10 of the sites in the network relative to an 11th site which is shown as a large filled circle. The 95% confidence ellipses are shown on the ends of the velocity vectors.



Appendix B

RESULTS FROM A GPS GEODYNAMIC NETWORK IN THE TIEN SHAN MOUNTAINS, KYRGYZSTAN AND KAZAKHSTAN, CIS

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During June-July 1993, we established an 86-site regional GPS network in the Tien Shan mountains of Kyrgyzstan and Kazakhstan. The network complements and extends a regional GPS network established by a German-CIS team in 1992, and consists of a broad, north-south profile across the central Tien Shan and a cluster of sites surrounding the Talas-Fergana fault. Semi-continuous measurements at sites located at distances of 100 to 400 km show day-to-day repeatabilities at the sub-cm level for the horizontal components. Remeasurement of a smaller, 13-station sub-network installed by our group in southeastern Kazakhstan and northwestern Kyrgyzstan in 1992 provide preliminary estimates of the rate of convergence across the the northern margin of the Tien Shan. Our longest north-south baseline, extending across the mountain front and repeatedly measured during both observation campaigns, appears to have shortened by 7 mm between the two surveys. If this convergence is representative of the overall shortening rate across the orogen, it would imply convergence between the Tarim Basin and the Eurasian plate at a rate of ~21 mm/yr.

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